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Towards operational mapping of solar radiation from Meteosat images

C. Rigollier & L. Wald
Groupe Télédétection et Modélisation, Ecole des Mines de Paris, Sophia Antipolis, France

ABSTRACT: Maps of solar energy are required in many fields such as agro-meteorology, climatology, and renewable energies. The objective of our project is to compute a climatological database of solar radiation over Europe, Africa, and Atlantic Ocean based on satellite observations. In order to develop such a climatology, the already existing Heliosat method has been chosen. Being one of the most accurate available method, the Heliosat method presents the great advantage over others of being easy to use. This method, used world-wide, makes use of geostationary satellite images to determine solar radiation at ground level. The present study proposes some improvements of the standard Heliosat method. Indeed, a few aspects of the approach should be improved in view of routine operation.

1. INTRODUCTION

This study is the first part of a project which aims at establishing solar radiation maps over Europe, Africa, and Atlantic Ocean, from 1985 up to now. Various methods allow to compute such a climatological database. The most relevant one according to our needs appears to be the Heliosat method, a widespread method in the scientific community.

This method makes use of satellite images of Meteosat to derive a cloud index, which characterises the transmittance of the atmosphere. This results from the comparison at a given pixel between what is observed by the sensor and what would be observed in clear sky conditions. This cloud index is then related to the atmospheric clearness index, which provides hourly global radiation.

Before any operational use of this method, some improvements are needed. Thus, we present here some modifications to the original method in order to increase accuracy, reliability, robustness, and independence. Product, an other essential aspect, is already well handled in the Heliosat method.

Underneath, after the reasons why the Heliosat method has been chosen, we briefly present this method, and then the improvements that can be applied.

2. HOW TO MAP SOLAR RADIATION AT GROUND LEVEL ?

2.1 Interpolation of ground stations measurements

Several works have been made to estimate solar radiation by spatial interpolation of the measurements routinely made at ground stations. Their findings are partly reported here.

Anonymous (1995), in a report to the MARS project, found that using 8 neighbouring stations to predict the daily sum of solar irradiation in a given site, may lead to a relative error (RMSE) of about 20 per cent. It is underlined that the bias (MBE) is often significant, and that the quality of the interpolation depends upon the geographical area. Supit (1994) reports on RMSE of about 15 - 25 per cent for five stations, using different techniques.

The most complete work has been made by Zelenka *et al.* (1992). They studied several advanced techniques applied to several networks of ground stations in Europe and Northern America. The gravity interpolation technique (using the square of the distance) provides estimates of the daily sum of global irradiation with a relative bias (MBE) of about 1 - 3 per cent, and a relative error (RMSE) ranging between 40 (January) to 15 per cent (July).

Hulme *et al.* (1995) for the sunshine hours, and Beyer, Wald (1996) for the daily irradiation, found similar results. They used respectively about 800 and 600 stations over Europe and dealt with climatological means (*i.e.* average over several years, respectively 30 and 10 years) of monthly average of daily sums. The relative bias (MBE) of the interpolated estimates is about 0 - 2 per cent, and the relative error (RMSE) ranges from 11 (January) to 5 per cent (July).

All authors used quality-controlled measurements for their studies. They underlined that introducing ground stations of low-quality as knots of the interpolation scheme, will result into a lower quality of the interpolated estimates. Therefore, ground measurements should be carefully checked before interpolation.

To assess the quality of the interpolation, authors compared interpolated estimates to ground measurements at sites which have not been used for interpolation. These sites are always located within the geographical area defined by the stations used for interpolation. Therefore the reported results can be considered as the best case. If a site is located outside this geographical area (e.g., extrapolating global radiation for Eastern Europe or Northern Africa using ground stations in Western Europe), the quality of the estimates will be low. Several authors (Zelenka *et al.*, 1992; Hay, Hanson, 1985; Hay, 1984; WMO, 1981, Perez *et al.*, 1997, Zelenka *et al.*, 1998) reported that extrapolation RMSE has been found to be a function of the distance of the site under concern to the stations. The larger the distance, the greater the RMSE. According to the relationship given in Zelenka *et al.*, the relative RMSE (in per cent) is about 10 at a distance of 16 km, about 20 at 64 km, and about 40 at 256 km. Such errors are very large.

Actually the situation is only slightly better in the case of interpolation, that is if the site under concern is 'surrounded' by ground stations. According to Zelenka *et al.*, the relative RMSE (in per cent) is about 10 at a distance of 16 km, about 18 at 64 km, and about 28 at 256 km. These errors are smaller than for extrapolation but are still large. In Eastern Europe, the distance between stations measuring the global radiation may be up to 5 degrees of arc angle, that is about 550 km. It is emphasised by several authors that accuracy may decrease if the stations used for interpolation are located into two different climatic areas, or if they are separated by some physiographic structures (e.g., interpolation from coast to island, stations separated by mountains, ...).

2.2 *Estimates from satellite images*

On the other hand, it exists several methods allowing to determine solar radiation at ground level from images of geostationary satellites. Furthermore, the estimates made from satellite data always offer the same quality within the observed area. It has been shown that they do not depend upon the geographical area, except for highly variable orography areas. For the latter cases, there is a strong dependence of the quality upon the spatial resolution of the satellite data: the better the resolution, the better the estimates (see e.g. Zelenka, 1994, for the case of Switzerland).

It is concluded that satellite estimates may currently offer the same, or even better, quality than those provided by interpolation within networks of ground stations. For extrapolation, *i.e.* outside a network, satellite estimates are definitely better. Therefore, we have chosen this way to map solar radiation.

In order to select an appropriate method, we stress out that the operational computation of a climatological database over several years requires:

- Accuracy. It is the essential quality for such a method. Better than twenty per cent (relative root mean square error) for daily sums and 10-days period sums, and 10 per cent for monthly average of daily sums are expected. Mean bias error should be close to 0.
- Reliability. Algorithms should be capable of producing maps of same accuracy over an extended period of time without external adjustment. This includes taking into account changes in sensor calibration and changes in sensor (e.g., the Meteosat series, from 1 to 5), but also changes of natural events like a volcano explosion and the resulting dust layer.
- Robustness. Algorithms should be capable to perform on different data sets (different space resolutions, different time sampling, different satellites, different sensors). Accordingly, interval parameters should be well described in relationship with physics, so as to be efficiently adapted in a new operational environment.
- Independence. Preferably algorithms should not call upon external sources of information while in operation.
- Applicability to large areas. Algorithms should be capable to map wide areas. This also implies considering required disk space, memory space, and computing time.
- Product. Algorithms should be capable of producing daily sums from which 10-days or monthly averages can be derived.

Table 1 displays accuracies obtained for various methods found in the literature or reported in personal communications. Those published by the founders while setting up the methods and successive versions have not been used for a better objectivity. Among these methods, the Heliosat method makes use of Meteosat images to estimate solar radiation. It is a well-known method. Its accuracy, qualities and drawbacks are known (Beyer *et al.* 1996; Cano 1982; Cano *et al.* 1986; Demarcq 1985; Diabaté *et al.* 1988, 1989; Diabaté 1989; Grüter *et al.* 1986; Moussu 1988; Moussu *et al.* 1989; Obrecht 1990;

Table 1. Accuracy of Heliosat and others reported in the literature and personal communications. Results for USA have been found in Zelenka *et al.* (1992). Negative MBE means overestimation.

Type	Reference	Relative mean bias error	Relative root mean square error
Hourly sum	Satellight project (CEC, DG 12) (Heliosat)	approx. 10 %	approx. 30 %
	Bauer (1996) (Heliosat, B2 format)	2 %	35 %
	Ielhé *et al.*(1997) (Heliosat)	18 %	30 %
Daily sum	Beyer *et al.* (1996) (Heliosat)	- 5 %	23 %
	DWD (method Möser, Raschke, 1983, 1984)	- 4 %	17 %
	Zelenka *et al.* (1992) (Heliosat)	- 10 %	16 %
	NOAA AgriSTARS (GOES sat.)	- 7 %	20 %
	NOAA AgriSTARS (GOES sat.) - Northeast of USA	- 2 %	21 %
Monthly means of daily sums	Solar Radiation Atlas of Africa (Cologne method)	2 %	10 %
	Solar Radiation Atlas of Africa (Heliosat)	- 8 %	10 %

Michaud-Regas 1986; Solar radiation atlas of Africa 1991; Zelenka 1986, 1994; Zelenka, Lazic 1987; Zelenka *et al.* 1990, 1992). One can see that Heliosat compares well with other methods for accuracy.

In addition, the Heliosat method is easy to use: this is an important advantage in the framework of a climatological database. Besides, Heliosat is, or has been, in operation in several places over the world. Therefore it can be stated that Heliosat is in principle compliant with all the above-mentioned requirements but one: it cannot accommodate for the change in sensor (*i.e.* change in Meteosat satellite) without the intervention of experienced people. Additionally there are some other weak points which may be improved in the method which relate to accuracy and robustness.

The Heliosat method, as one of the most accurate methods, presents the quality of being easy to use, and has been chosen to map solar radiation over Europe, Africa, and Atlantic Ocean from 1985 up to now. But, it should be improved for a better quality and operationality. After a brief description of the Heliosat method, we will propose some improvements of the current method.

3. THE HELIOSAT METHOD

The method presented here slightly differs from the original one from Cano *et al.* (1986). It makes use of meteorological satellite images to estimate solar irradiation.

From the digital count of the given METEOSAT image (DC), we can compute the apparent albedo ρ^t for each pixel of the image at the time t:

$$\rho^t = (DC - DC0) / G_c^t \qquad (1)$$

where:

- $DC0$ represents the sensor offset, when the sensor is not calibrated.
- G_c^t is the global irradiance under clear-sky. Cano *et al.* (1986) used the model of Bourges (1979):

$$G_c^t = 0.7\, I_0\, \varepsilon\, (\sin \gamma_S)^{1.15} \qquad (2)$$

while Moussu *et al.* (1989) used a very similar one, but from Perrin de Brichambaut and Vauge (1982).

- $I_0 = 1367\ W.m^{-2}$ is the solar constant.
- ε is the correction of the sun-earth distance.
- γ_S is the solar elevation (in degrees).

Then, we can derive a cloud index n^t, which characterises the transmittance of the atmosphere. This index results from the comparison at a given pixel between what is observed by the sensor (ρ^t) and what should be observed in clear-sky conditions (ρ):

$$n^t = (\rho^t - \rho)/(\rho_c - \rho) \qquad (3)$$

The value of ρ is obtained by taking the minimum value of apparent albedo for each pixel for a given time-series of images. It results into a map of apparent albedo under clear-sky conditions. By the same way, we can obtain the value of the apparent albedo of the brightest clouds, ρ_c by taking the maximum value of the image.

This cloud index, n^t is then related to the atmospheric clearness index, K_c^t by the relationship proposed by Beyer *et al.* (1996):

$$K_c^t = 1 - n^t \qquad (4)$$

The clearness index is defined as the ratio between the global solar irradiation, G^t and the clear-sky global solar irradiation, G_c^t (on an horizontal surface). So, we can provide the hourly sum of global solar irradiation at ground level:

$$G^t = K_c^t\, G_c^t \qquad (5)$$

4. TOWARDS OPERATIONAL USE OF THE HELIOSAT METHOD

Mapping solar irradiation over an extended period of twelve years, and over a large area which covers Europe, Africa, and Atlantic Ocean, requires several aspects described previously. It requests a few improvements of the Heliosat method. Three improvement points are described below. The first one has been investigated because of the extended period of twelve years. Indeed, after a change of satellite sensor, the digital count of the image from the first sensor is not calibrated against to the digital count of the image from the second sensor. Yet, five different Meteosat sensors have been used since 1985. Hence, the calibration function has been studied.

The second point deals with the clear-sky model. A new one has been selected which is much more accurate than the previous ones. However, it requires a better description of the climatological optical state of the atmosphere by the means of the Linke turbidity factor which is not easy to measure anywhere in the world. It also requests the elevation of the site.

The last improvement point presented here concerns the relationship between the cloud index and the global radiation. As a matter of fact, when comparing the estimated values and the ground measurements for overcast skies, a discrepancy is noted and should be removed.

4.1 The calibration function

The calibration function is the relationship between the digital count of the image and the amount of energy received by the satellite. In the realisation of a climatological database, the calibration function has a significant interest. Indeed, we have to process a large time series of images (twelve years of data). During this long period, five different Meteosat sensors have been used, involving changes in the digital count.

We have designed and tested an automatic method which applies on each individual image and converts the digital counts into radiance ($W.m^{-2}.st^{-1}$). The method is based on a statistical analysis and, given a time series, it requires only one calibrated image. This image may be taken at any moment and can be selected according to the publications made on that subject. The method has been extensively tested using published calibration functions. It provides accurate results and is robust and reliable. (Lefèvre *et al.* 1998).

4.2 The clear-sky model

This new model of clear-sky irradiation has been set up in the course of the realisation of the 4th edition of the European Solar Radiation Atlas (1998).

The better the clear-sky model, the better the assessment of the irradiation from satellite observations. Compared to the models used in the previous versions of Heliosat, there is an explicit expression for both the beam and the diffuse components. The parameters of this model have been empirically adjusted by fitting techniques using hourly measurements spanned over several years and for several locations in Europe. The Linke turbidity factor (T_L) is a key point in this model. It is a function of the scattering by aerosols and the absorption by the gas, mainly water vapour. When combined with the atmosphere molecules scattering, it summarises the turbidity of the atmosphere, and hence the attenuation of the direct beam and the importance of the diffuse fraction. The larger the Linke turbidity factor, the larger the attenuation of the radiation by the clear sky atmosphere.

In this model, the global clear-sky irradiation is given by the following equation:

$$G_c = B_c + D_c \qquad (6)$$

where:

- $B_c = I_0\, \varepsilon \sin \gamma_S \exp(-0.8662\, T_L\, m\, \delta_R)$ $\qquad (7)$

  is the beam component of the horizontal global irradiance under cloudless skies. In this expression, m is the relative optical air mass, and δ_R is the integral Rayleigh optical thickness. The quantity $\exp(-0.8662\, T_L\, m\, \delta_R)$ represents the beam transmittance under cloudless skies. The hourly beam horizontal irradiation can be obtained by numerical integration of the beam irradiance (equation 7) for a period equal to one hour.

- $D_c = I_0\, \varepsilon\, T_{rd}(T_L)\, F_d(\gamma_S, T_L)$ $\qquad (8)$

  is the diffuse component. The transmission function at zenith (i.e. sun elevation is 90°), T_{rd} is given by:
  $T_{rd} = -1.5843\ 10^{-2} + 3.0543\ 10^{-2}\ T_L + 3.8\ 10^{-4}\ T_L^2$
  Typically, T_{rd} ranges from 0.05 ($T_L = 2$) for clear-sky to 0.22 ($T_L = 7$) for very turbid atmosphere.
  F_d is a diffuse angular function:
  $F_d(\gamma_S, T_L) = A_0 + A_1 \sin \gamma_S + A_2 (\sin \gamma_S)^2$
  The coefficients A_0, A_1, and A_2 only depend on the Linke turbidity factor. They are unitless and are given by:

$$\begin{cases} A_0 = 2.6463\,10^{-1} - 6.1581\,10^{-2}\,T_L + 3.1408\,10^{-3}\,T_L{}^2 \\ A_1 = 2.0402 + 1.8945\,10^{-2}\,T_L - 1.1161\,10^{-2}\,T_L{}^2 \\ A_2 = -1.3025 + 3.9231\,10^{-2}\,T_L + 8.5079\,10^{-3}\,T_L{}^2 \end{cases}$$

Finally, the diffuse horizontal irradiation is computed by the analytical integration of the diffuse irradiance (equation 8) over a period of one hour.

4.3 The relationship between the clear-sky index and the cloud index

The relationship given by equation 4 yields acceptable results with the advantage of simplicity. But, for cloudy sky cases several comparisons show large discrepancies between the estimation obtained with the Heliosat method and the observations made with ground stations. So, for overcast skies (cloud index values near to 1), the model $K_c^t = 1 - n^t$ seems to be not suitable. A second order polynomial function appears more relevant for cloudy skies. Hence, the relationship between the clear-sky index and the cloud index becomes:

$n^t < -0.2$	$K_c^t = 1.2$
$-0.2 < n^t < 0.8$	$K_c^t = 1\text{-}n$
$0.8 < n^t < 1.1$	$K_c^t = 2.0667\text{-}3.6667n^t\text{+}1.6667(n^t)^2$
$n^t > 1.1$	$K_c^t = 0.05$

as shown in the figure 1.

This function is continuous. Its first derivative is also continuous, but for n = -0.2.

5. CONCLUSION

We have proposed modifications for the current Heliosat method in order to improve its quality and

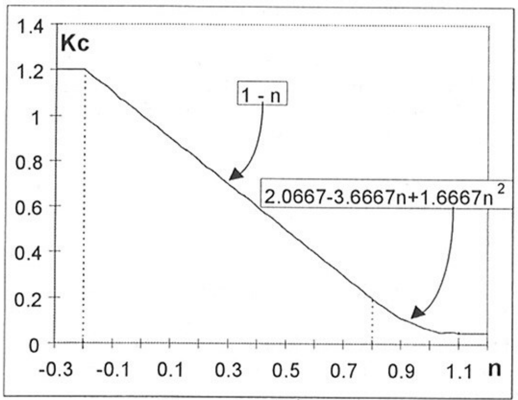

Figure 1. $K_c^t = f(n^t)$

routine operation. Thus, mapping of solar irradiation during twelve years will be achieved. To validate these improvements, and the new version of the Heliosat method, the estimated values of global solar irradiation will be compared with ground measurements on both hourly and daily basis. Once the new Heliosat method accepted, we will test its behaviour on Meteosat data of reduced resolution: the B2 format. Finally, we will apply it to a large database of Meteosat B2 images to obtain a climatological database of solar radiation over Europe, Africa, and Atlantic Ocean.

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